“The Durability of Polymeric Encapsulation Materials for Concentrating Photovoltaic Systems”

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2012 PV Module Reliability Workshop
(Denver West Marriot, Golden, CO)
8:30-8:50 am, 2012/3/01 (Thursday)
Golden Ballroom

-this presentation contains no proprietary information-

NREL/PR 5200 54524
Motivation for the NREL Field Study

- Concentrating Photovoltaic (CPV) modules use cost effective optics ($) to focus light onto high efficiency ($\eta=44\%$) multijunction cells ($$$$$$

Cross-sectional schematic of the components near the cell in CPV systems (not to scale)
Motivation for the NREL Field Study

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**cross-sectional schematic of the components near the cell in CPV systems (not to scale)**

**corrosion prevention, optical coupling:** CPV systems typically use encapsulation to adhere optical component(s) or cover glass to the cell
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• Concentrating Photovoltaic (CPV) modules use cost effective optics ($) to focus light onto high efficiency ($\eta=44\%$) multijunction cells ($$$$$$)

corrosion prevention, optical coupling: CPV systems typically use encapsulation to adhere optical component(s) or cover glass to the cell.

encapsulation durability (30 year field deployment) is unknown:
• identify field failure modes
• gain insight related to failure mechanisms
• distinguish between material types
• identify materials for future study (HALT & qualification tests)
Details of the Experiment (Specimens & Apparatus)

Miller et. al., PIP, DOI: 10.1002/pip.1241.

**Table: Materials in Test**

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>ON-TEST</th>
<th>IN QUEUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVA</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>ionomer</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>polyolefin</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>PVB</td>
<td>2</td>
<td>0</td>
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<tr>
<td>TPU</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>PDMS</td>
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<td>5</td>
</tr>
<tr>
<td>PPMS</td>
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<td>1</td>
</tr>
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<td><strong>TOTAL</strong></td>
<td><strong>25</strong></td>
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**Notes:**
- Hydrocarbons (representative types)
- Silicones (representative grades)

*test coupons are mounted in a modified CPV module product on a 2-axis tracker in Golden, CO*
Details of the Experiment (Specimens & Apparatus)

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Secondary optic (homogenizer)

Test coupons are mounted in a modified CPV module product on a 2-axis tracker in Golden, CO.
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**Table: MATERIAL vs. ON-TEST vs. IN QUEUE**

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**Notes:**
- **Silicones (representative grades):**
  - **silicones**
  - **hydrocarbons (representative types):**

**Discussion:**
- Test coupons are mounted in a modified CPV module product on a 2-axis tracker in Golden, CO.
- Passive cooling; no cell.
- **h=5 mm:** Not advised in future research.
- **C_g = 500x**

**Images:**
- Hydrocarbon
- Quartz/encapsulation/quartz
- Silicone

**Legend:**
- incident solar flux
- domed Fresnel lens
- reflector/aperture
- kaleidoscope homogenizer
- silica superstrate & substrate
- polymeric specimen
- aluminum base
- anodized machine screw
- secondary optic (homogenizer)
- domed PMMA Fresnel lens

**References:**
- Innovation for Our Energy Future
- Miller et al., PIP, DOI: 10.1002/pip.1241.
Details of the Experiment  (Measurands & Schedule)

“Continuous” measurements:
- ambient conditions (irradiance, temperature, wind...)
- fixture temperature (via thermocouple)

Periodic measurements:
- transmittance ($T[\lambda]$, hemispherical & direct)
- mass
- appearance (photograph)

> from $T[\lambda]$, calculate: yellowness index (D65 source, 1964 10° observer), haze, $\lambda_{\text{cut-on}}$ ...

> fluorescence spectroscopy

Final measurements:
- FTIR, RAMAN, NMR
- TGA, DSC (polymer physics)

Test schedule:
0, 1, 2, 4, 6, 12, 18, 24, 30, 36 ... months
Optical Irradiance May Vary from CPV Transmittance

- PMMA transmits little \((T=1\%)\) UV flux, \(\lambda>390\) nm
- Thermal content therefore has increased significance (coupled UV & thermal degradation)

- Some popular indoor sources (UV 313V, UV340A) are completely inappropriate for a PMMA-enabled CPV system
- SoG Fresnel lens is substantially more transmitting \((T=89\%)\) of UV

Miller et. al., PIP, DOI: 10.1002/pip.1241

Irradiance for popular optical sources (including the sun) relative to the CPV optical system
UV Radiation: Damaging Dose

- Early weathering studies ⇒ total UV dose (damage vs. Joules or hours)

- Activation spectrum instead considers:
  1. characteristics of source & optical system
  2. effectiveness of damage at each λ ("action spectrum")
  3. may be unique to each characteristic (+ and -)

\[ \Lambda[\lambda] = E[\lambda]s[\lambda] = E[\lambda]c_1e^{-c_2\lambda} \]

\[ E[\lambda] = E_l[\lambda]C_g\prod_{i=1}^{i=j}\eta_iT_i[\lambda]\prod_{k=1}^{k=l}\eta_kR_k[\lambda] \]

Miller et. al., Optical Engineering, 50 (1), 2011, 013003
The Optical System Readily Affects UV & IR Dose

Innovation for Our Energy Future

Miller et. al., Optical Engineering, 50 (1), 2011, 013003
The Field Conditions (Specimen Temperature)

- Specimen temperature proportional to optical (IR) absorptance (thermal management “system”: conduction to the frame.)
- Measured at solar noon. Factors: $T_{\text{amb}}$, irradiance, wind speed
- ~40°C temperature rise observed. $T_{\text{max}}$ 70-80°C in summer.

**Graph Description:**
- $T_{\text{meas}}$, measured temperature [°C] vs. $T_{\text{amb}}$, ambient temperature [°C]
- Linear relationship: $T = 0.66T_{\text{amb}} + 38$
- PDMS specimen temperature, determined using optical thermography

*Miller et. al., PIP, DOI: 10.1002/pip.1241.*
Thermal Decomposition of the Encapsulation May Occur at High Temperature

- Thermal stability compared using thermogravimetric analysis (TGA) @20°C·min⁻¹

- Onset of decomposition for hydrocarbons: 200-300°C

- Silicones more thermally stable: $T_{\text{onset}}$ 300-400°C

*Remember $T$’s for later!*

Thermography data for representative materials from the study

Miller et. al., PIP, DOI: 10.1002/pip.1241
Results of Discovery Experiments
(The Homogenizer)

**EVA:** without homogenizer, rapid discoloration \(\Rightarrow\) combustion

optical images of EVA in (a) & (b), and PDMS in (c).
inset shows: voided center, char, cracked cover-glass, discoloration, delamination

**silicone:** without homogenizer \(\Rightarrow\) combustion

- Likely motivated by local hot spots \((10^1\) to \(10^3\) \cdot C_g)\)

Results of Discovery Experiments
The Effect of Contamination

• Intentionally introduce soil, Al, PE, or bubbles into EVA or silicone

**EVA:** soil, Al, PE motivated localized discoloration $\Rightarrow$ combustion

**silicone:** soil, Al $\Rightarrow$ localized cracking. (no primer present)

• elapsed time: minutes – days/weeks

• bubbles: no failure @ $C_g$=500, despite 4% measured $T[\lambda]$ reduction

*Innovation for Our Energy Future*
Results of the Formal Experiment
(Hydrocarbon Specimens)

- PVB was the first material to demonstrate thermal runaway mediated failure
- The radius of the affected region was seen to slowly grow during the cold winter months

optical images of test specimen at:
(a) 6 months and (b) 10 months

Miller et. al., PIP, DOI: 10.1002/pip.1241

time sequence: optical images of test specimen

(1) 06 months, (2) 07.5 months, (3) 08.5 months, (4) 09 months, (5) 10 months

200 μm
Results of the Formal Experiment
(Hydrocarbon Specimens)

- Transmittance & YI not significantly affected, despite impending failure
- A diagnostic characteristic with predictive capability is preferred!!!

The optical fluorescence spectrum of PVB, for $\lambda = 280$ nm

time sequence: transmittance of the PVB specimen
Results of the Formal Experiment
(Hydrocarbon Specimens)

- Transmittance & YI not significantly affected, despite impending failure
- A diagnostic characteristic with predictive capability is preferred!!!

- Optical & Raman spectroscopy clearly indicate fluorescence
- These techniques may help understand the degradation mechanism (e.g., chromophores)

*optical fluorescence spectrum of PVB, for $\lambda_f = 280$ nm*
Results of the Formal Experiment
(Silicone Specimens)

- Observations of silicone specimens include: (a) densification, (b) cracking, and (c) haze formation
  - No mass change with time for the (5) **densified** specimens ⇒ likely occurred during molding

- **Crack** advancement occurred during cold weather periods only ⇒ likely motivated by CTE misfit
- Additional fractured specimens may be emerging

**Haze** formation is attributed to one material’s unique formulation

*optical images of silicone specimens, including those obtained using (a) cross-polarization or (c) back-lighting*
Results of the Formal Experiment
(Densified Silicone Specimens)

- Densification is not delamination
- Densification does scatter direct light

Problematic for CPV?
- Current limited condition (blue light) • Optical attenuation (less power)
⇒ May not be significant in thin bond layers

Miller et. al., PIP, DOI: 10.1002/pip.1241

Innovation for Our Energy Future
Fluorescence Identifies the Silicones Are Affected!

- Unexpected new peaks identified for all silicone specimens!
- The particular details location and relative intensity of the new $M_t$ peaks varied with formulation.
- Attributed to Pt catalyst (working to verify).

- The implications are unclear. PDMS is historically robust in extreme environments. $\lambda_x < 390$ nm for PMMA, $\sim 320$ nm for SoG.
UV and/or Temperature Can Degrade Pt Catalyst

• Karstedt’s catalyst, Pt(0), examined in tetramethyldivinyldisiloxane
• Catalyst loses fluorescence with UV or T
• Organometallic literature: mononuclear Pt with ligands → colloidal Pt, 3-5 nm

• Discoloration (optical absorptance) could motivate thermal runaway

• No evidence to date of optical degradation in NREL specimens
• Fluorescence of catalyst solution does not correspond to that in x-linked PDMS

• Alternate pathways: different catalyst type (ligands), peroxide cured silicone, PMMA on glass (PoG) lenses, AR coatings
UV Can Degrade Silicone Primers

- Dow-Corning 92-023 used in all NREL PDMS specimens
- The Ti based primer (on glass) reduces UV transmittance for $\lambda < 300$ nm ($n_{TiO_2} = 2.5$)

- Experiments identify primer is quite photoactive:
  - discoloration with minor fluorescence
- Transparency recovered with time ($O_2$ facilitated?)

- $TiO_2$ used in self cleaning coatings.
  (UV driven consumption of organic contamination). Affect on PDMS is unclear.
- Alternate pathway: Sn catalyzed primers ($n_{SnO}=2.1$)
Summary & Conclusions

Field study of the durability of polymeric encapsulation materials for CPV

Discovery experiments:
• Quickly confirmed the importance of an optical homogenizer
• Al, soil, polymeric contamination ⇒ $T$ runaway & combustion of EVA
• Al, soil contamination ⇒ cracking of silicone

Formal experiment:
• 17 of 25 specimens not discussed today!  
  • 3 of 25 specimens “failed”.

PVB: localized discoloration ⇒ thermal runaway ⇒ combustion
Fluorescence & Raman spectroscopy may diagnose & provide prediction
Silicone: densification, cracking, haze-formation
Densification affects the direct transmittance

PDMS Fluorescence:
• Working to understand observed peaks; alternative “solutions” identified

* Transmittance of optical system and corresponding activation spectrum of the encapsulation are critical to encapsulation durability
Acknowledgements

- NREL: Dr. Keith Emery, Dr. Daryl Myers, Dr. John Pern, Matt Beach, Christa Loux, Tom Moricone, Marc Oddo, Bryan Price, Kent Terwilliger, Robert Tirawat

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